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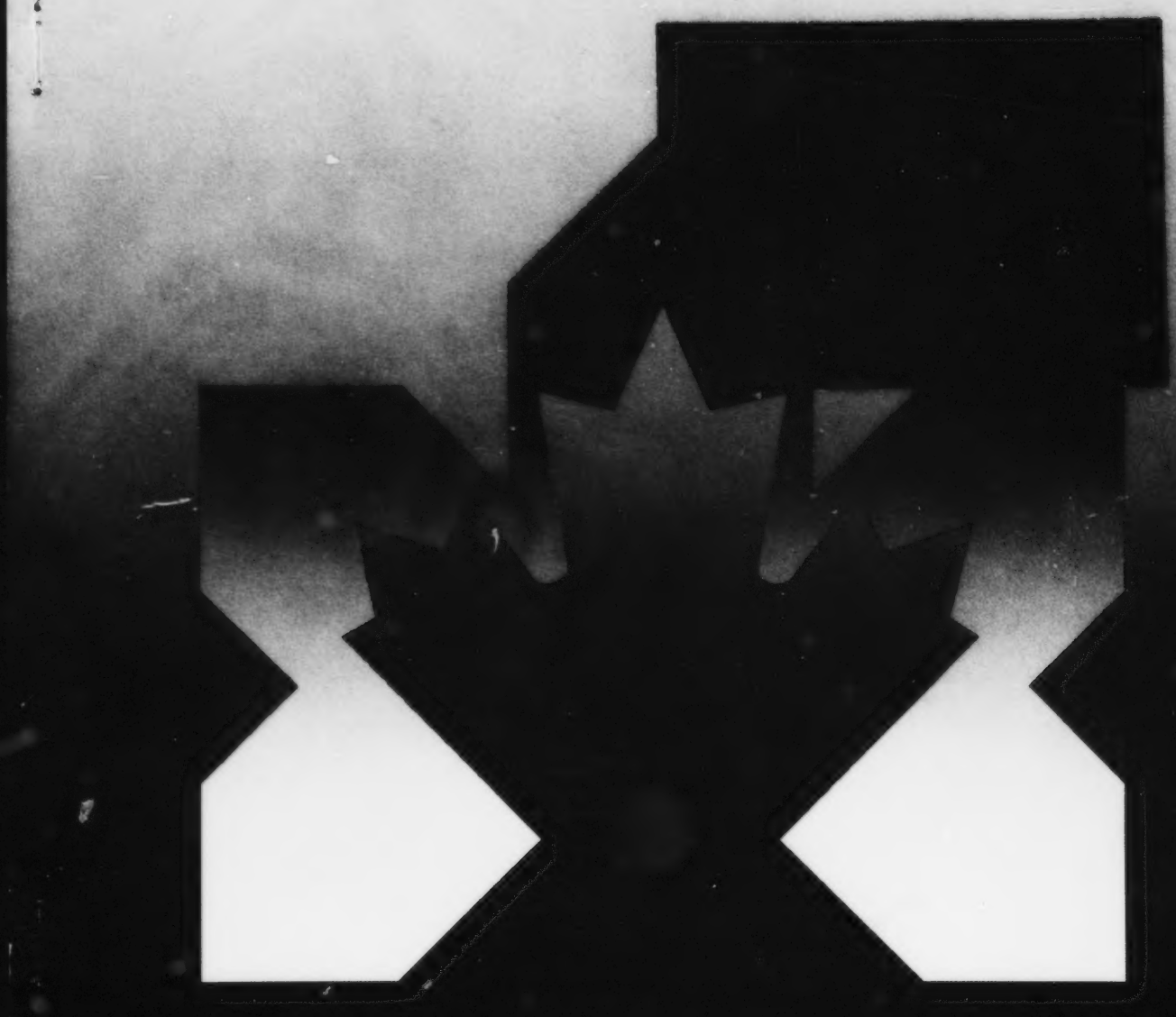

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ASSESSMENT of EARTHQUAKE EFFECTS on RESIDENTIAL BUILDINGS and SERVICES in the GREATER VANCOUVER AREA

February 1989

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CLIENT REPORT

for

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Assessment of Earthquake Effects on Residential Buildings and Services in the Greater Vancouver Area

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ASSESSMENT OF EARTHQUAKE EFFECTS ON RESIDENTIAL BUILDINGS AND SERVICES IN THE GREATER VANCOUVER AREA

EXECUTIVE SUMMARY

On the basis of previous earthquake damage, mainly in California and Alaska, an assessment is made of the effects on residential buildings in the Greater Vancouver Area during and after an earthquake. Two levels of earthquakes are considered:

a) the "design level earthquake" of the National Building Code of Canada, 1985 Edition;
b) a "major earthquake" corresponding to a slip of the tectonic plates along the west coast of British Columbia, also called a "major subduction earthquake".

The design level earthquake is characterized by a peak ground acceleration of 0.20 times the gravitational acceleration (g). The location, magnitude, recurrence interval, and the resulting ground motions of the subduction earthquake are somewhat uncertain. For such an earthquake a peak ground motion acceleration amplitude of 0.50 g in the Vancouver area has been assumed.

The resulting damage picture is as follows:

a) Design level earthquake: It is estimated that from 5-10% of residential buildings would be uninhabitable immediately after the earthquake. Within a few weeks, however, a majority of these should become habitable as a result of repairs and strengthening. For unreinforced masonry and pre-1940 schools and hospitals up to 50% would likely become uninhabitable and some would collapse, with significant casualties. It is estimated that 5-10% of the sewers, water supply, electricity and transportation route would be damaged and services interrupted. Some areas in the alluvial Fraser River delta would suffer liquefaction and exhibit sand boils, occasional slumping of dykes and differential settlements of some of the small buildings. This liquefaction would cause some damage to runways, but is not expected to affect the airport structures significantly. Some communication systems such as telephone, radio and radar would be inoperative.

b) Major Subduction Earthquake: About 10-30% of residential construction would become uninhabitable and up to 30% of transportation routes unusable. 50-100% of unreinforced masonry buildings would collapse. Up to 60% of older schools and hospitals (pre-1940) that have not been strengthened, and many utilities would become unusable. In alluvial sand deposits, liquefaction would be widespread, causing sinking or tipping of many major buildings, and slumping of dykes. The concentration and extent of major damage would be greater in areas of soft soil deposits than in areas having rock or hard foundation materials. Communications would be severely disrupted and major damage inflicted on runways. Airport buildings and traffic control would also suffer substantially.

The extent of damage for the postulated major subduction earthquake could well be termed "catastrophic". It is therefore of the greatest importance that the engineering properties and likelihood of occurrence of such an earthquake and specific hazards be more clearly defined; countermeasures can then be designed and implemented. Other recommended studies include the behaviour of specific types of buildings and soil deposits, and the development of a general evaluation procedure for the seismic vulnerability of buildings and subsequent strengthening program.

1. INTRODUCTION

The Greater Vancouver Area includes the City of Vancouver and adjacent municipalities of North and West Vancouver, Burnaby, Richmond, New Westminster and Surrey. The area is situated on the banks of the Strait of Georgia between the first ranges of Coast Mountains and arms of the Fraser River, which form the Fraser Delta (Fig. 1). This metropolitan area is heavily populated and comprised of all possible structures, from high-rise buildings to single family dwelling houses. It is located adjacent to one of the highest risk earthquake zones in Canada.

This report covers preliminary studies concerning the nature and extent of the impact of earthquakes in the Greater Vancouver Area on both residential structures and supporting services.

Experience gained from past earthquakes in other regions (mainly in California, Alaska and Central and South America) is used to predict the impact of earthquakes on typical Canadian single family, low-rise (2 to 4-story), medium-rise (5 to 9-story) and high-rise (> 10-story) residential structures.

Conclusions and recommendations for further studies are included.

As background and support material to this report, the Modified Mercalli Intensity Scale is presented in Appendix 1 and key technical words used in this report are explained in Appendix 2.

2. BASIC PARAMETERS

2.1 Classification of Failures

The classification of physical failures of all kinds (buildings, ground, facilities, lifelines, etc.) in the event of an earthquake must be related to the primary concerns . These primary concerns are human safety, human health, emergency effectiveness and economic loss. For this purpose, all physical failures which impinge on these primary concerns can be classified into three categories depending on the consequences:

I - consequences severe and immediate (e.g., collapse of buildings, gas explosion, landslides or dam failures in hilly areas, sudden flooding, fire in high rise buildings);
II - consequences severe but not immediate (e.g., liquefaction, dyke failure, severe building damage - i.e. building must be abandoned temporarily, pole and tower collapse, transformer break, fire);
III - economic loss only (buildings cracked but not abandoned, facilities damaged, gradual flooding).

As an example, Type I building failures imply death and injury, Type II building failures imply loss of use, and Type III building failures imply economic loss.

All failures in past earthquakes can be classified in this way (unfortunately many are not) and, on this basis, the estimated consequences of future earthquakes can be estimated as a function of types of buildings, facilities, lifelines (gas, water, sewage, power and communication systems), and ground conditions.

The information on expected failure losses for a given earthquake will be expressed as loss ratios for each consequence category and for each type of building (e.g., wood housing versus modern highrise), facility or lifeline. These loss ratios can then be used to estimate primary losses - i.e. deaths, injuries, health hazards, and economic losses of various kinds.

In the period of time available for this contract, it is not possible to estimate such data with any consistent accuracy, but a start in this direction is made. What follows is background information directed toward this goal. The losses addressed here concern those of Types I and II building failures, i.e. loss of use accompanied by some deaths or injuries.

2.2 Restoration Time

In addition to classifying failures according to immediate and long-term consequences it is also important to estimate the time it takes to restore key lifelines and facilities for safety and health, and other facilities and lifelines for habitability and use. The longer the delay, the more it affects safety and health (including psychological), and the more it affects local economy. Restoration is both temporary for immediate use (e.g. polyethylene sheets for weather protection), which takes a minimum time and effort, and permanent for continued use.

The restoration time of a facility depends on physical damage to the facility, failure of key lifelines to the facility (e.g. communication for the operation of an airport), and the availability of materials, equipment and labour for repair which in turn depends on the total extent of earthquake damage. Previous studies (19) indicate that failure of lifelines is most significant and that the restoration times of failed lifelines can be estimated in terms of hours or days for electricity, days for water, gas and roads, and weeks for bridges.

3. PREDICTED EARTHQUAKES IN THE GREATER VANCOUVER AREA

3.1 General Comments

Earthquakes are caused by a sudden release of energy due to tectonic forces acting inside the seismically active zones of the earth's crust. The release of energy causes seismic waves to originate from the source of disturbance, the slip or fault zone.

The amount of damage depends upon many factors and some of them are listed below:

1) the amount of energy released,
2) the distance from the epicenter or fault,
3) the depth of the focal point (shallow or deep earthquakes),
4) the local geology of the site,
5) the building features, as for example the orientation of the structure and its engineering quality,
6) the soil-structure interaction.

The size or amount of energy released by an earthquake is usually expressed in terms of the open ended Richter Magnitude Scale, M. From the damage point of view, the significant range is between M5 to M9. The earthquake intensity is another measure of earthquake effects. The Modified Mercalli Intensity Scale is in use in the United States and Canada. The correlation between Modified-Mercalli scale and the average peak ground motion is presented in Appendix 1 (7,16).

Richter has correlated the Modified Mercalli Intensity Scale with the Richter magnitude (7); an approximate correspondence for the NBCC 1985 seismic zoning is also added here:

Magnitude M on Richter scale

2	3	4	5	6	7	8

Intensity I on Modified Mercalli scale for locations near the epicentre:

I-II	III	V	VI-VII	VII-VIII	IX-X	XI

Approximate corresponding seismic zoning, NBCC 1985

	1	2-3	3-4	4-5	5-6

The foregoing is a rough correlation "for ordinary ground conditions in metropolitan areas of California", and must be used with caution (7). However, the metropolitan area of Vancouver has some similar features to those of California and therefore for this broad survey the correlation is assumed to be applicable. It should be noted that while the magnitude of the earthquake is a unique quantity, intensity at a point depends upon several factors such as the magnitude itself (severity of an earthquake) and the distance from the causative fault or centre of the energy release (distance from the epicenter).

In this section an evaluation of the consequences of a design earthquake based on the National Building Code of Canada (NBCC - 1985) (9) is presented. Also addressed are damage characteristics for a "major earthquake" in the Greater Vancouver Area based on the recent data from Geological Survey of Canada (GSC), Dept. of Energy, Mines and Resources (EMR).

3.2 Southwestern Canada Earthquake Potential

Canada's southwestern coast is a part of the Circum-Pacific seismic belt, comprised of short ridge segments and faults separating the Pacific plate and the Juan de Fuca Explorer platelets (Fig. 2). These plate remnants are constantly moving under Vancouver Island and the Lower Mainland of British Columbia by a process called "subduction". Both American and Canadian geophysicists study this phenomenon.

The Juan de Fuca and North America plates appear to be converging at a rate of about 3-4 cm per year. The Juan de Fuca subduction zone is similar to other subduction zones (e.g. the Chilean subduction zone). However, the one striking feature of the Juan de Fuca zone is its present low level of seismicity (2). The shallowest parts of this zone are presently quiescent with respect to earthquakes of magnitude 4 or greater. There is no historical record of a large, most dangerous shallow earthquake along this particular zone. There is now sufficient evidence, however, that the possibility of great earthquakes exists in this area. According to D.H. Weichert and P.S. Munro (1) the potential of large earthquakes on the Juan de Fuca subduction interface must be seriously considered. The most recent information on this topic can be found in a paper by G.C. Rogers (4). Rupture of the entire Juan de Fuca subduction zone (referred to as Cascadia Zone) would be equivalent to a major earthquake of Richter magnitude M9.3. Within the Juan de Fuca subduction zone there are segments that may rupture independently. The independent subductions may lead to earthquakes of the following magnitudes: Nootka Fault Zone - M8.7, major part of the Juan de Fuca - M9.1-M9.2, South Gorda Zone (near California) - M8.3, Winona - M8.2 and Explorer - M8.5 (Figs. 2 and 3).

Further north, the Pacific-North American plate boundary consists of the Queen Charlotte fault, which has also a small subduction component near the Queen Charlotte Islands. A magnitude 8.1 earthquake took place in 1949 along this section of plate boundary.

Historically recorded earthquake zones extend from Seattle-Tacoma at the south part of the Puget Sound in the state of Washington, to about the 49th parallel, halfway between metropolitan areas of Vancouver and Victoria around the Gulf Islands. Several earthquakes near or above magnitude 7 on the Richter Scale have occurred within the subducting plate under Vancouver Island within a few hundred km of Vancouver. There is a relatively quiet zone to the north of 49°N, which is followed by a zone of moderate earthquakes (M3-M4) northwest from the Greater Vancouver Area. Large events with probable epicentres located in the vicinity of the Gulf Islands are considered to be the closest likely threat to the metropolitan areas (≈ 50 km) of Vancouver and Victoria (1,3).

3.3 Design Earthquake Based on NBCC (1985)

The seismic zoning maps in NBCC (1985) are based on a statistical analysis of the earthquakes that have been experienced in Canada and adjacent regions and on broad local geologic features. The data were analyzed using the Cornell method and a seismic risk program by McGuire (9). This analysis does not include the risk of a "major subduction earthquake" the possible importance of which has only been appreciated fairly recently. The probability of exceedance is 0.0021 per annum, which is equal to a probability of exceedance of 10 percent in 50 years. Based on Table J-2 from Commentary J to NBCC (1985), the peak horizontal acceleration (PHA) and the peak horizontal velocity (PHV) for the Vancouver area are listed below along with the probability of annual exceedance.

Table 1. Design Earthquake Values for Vancouver (firm ground)

Probability of exceedance per Annum (P)	Return Period (1/P, years)	Peak Horizontal Acceleration (PHA, g)	Peak Horizontal Velocity (PHV, m/s)
0.01	100	0.089	0.077
0.005	200	0.13	0.12
0.0021	475	0.21	0.21
0.001	1000	0.26	0.26

The Greater Vancouver Area is located in the acceleration-related seismic zone $Z_a = 4$, with zonal acceleration ratio a = 0.20.

3.4 Major Subduction Earthquake

The studies leading to the NBCC (1985) do not cover the potential of a "major earthquake", for which the peak horizontal acceleration values can reach the range of 0.3g - 0.8g in the Vancouver area. The expected event can have a long duration from 3 to 5 minutes, which is potentially dangerous for high-rise residential buildings. The prediction of a "major earthquake" is presented in Ref. 4. The expected magnitude of an event can reach M9.3, which can be a devastating experience in every aspect. The location of the epicentre is likely to be somewhere offshore of the Vancouver Island (≈100 km from the Vancouver area). For purposes of this study, the value of the peak horizontal acceleration is taken to be 0.5g without amplification due to specific ground conditions; the magnitude is taken as M8.5. This corresponds to the partial subduction of the Juan de Fuca Plate (Fig. 2), which is a part of the Cascadia subduction zone (Fig. 2). However, the danger of total rupture of the entire plate boundary with a magnitude M9.3 cannot be completely ruled out. The different earthquakes originating within the Cascadia subduction zone have already been summarized in Section 3.2 of this report. The subduction

zones around the Pacific are highlighted in Fig. 3 (from Ref. 4). The big events and their magnitudes are also indicated. The assumed major subduction earthquake (M8.5) has a return period of about 600-1000 years.

4. SOIL CONDITIONS AND LIQUEFACTION

4.1 General Comments

Two major effects can arise when soils are subjected to earthquakes: 1. motion amplification (or in rare cases, a reduction) as the seismic motions propagate from the bedrock to the surface; 2. soil liquefaction due to ground shaking.

Motion amplification is caused by a resonance effect of the soil layers, resulting in increased surface motion as compared to the motions that arrive in the bedrock beneath. A notable example of motion amplification occurred in the Mexico City earthquake of 1985 (22). Whether similar effects could occur in the Vancouver area is not yet fully established due to the complex geometry and material properties. Further investigations are needed to clarify this aspect.

Soil liquefaction may arise when saturated granular or cohesionless soils are shaken, resulting in a loss of strength. At this state the soil will behave like a liquid. This results in building settlement or tipping, sand boils, ground cracks, landslides, dam instability, highway embankment failures or other hazards. Some of these hazards have been documented by Rogers (10) for the British Columbia earthquake of 23 June, 1946.

4.2 Soil Conditions in the Greater Vancouver Area

The geology of the Greater Vancouver Area is known (5,6) and the area is underlain by thick clays, followed by sands, silt-clay deposits on the bedrock, or bedrock itself in some areas North of the Fraser River. There is a certain variability in soil conditions between the Fraser Delta and Burnaby Ridge in the north-south direction and also between the Fraser Delta and the eastern part of Surrey. The location of the soft Fraser Delta deposits is presented in Fig. 4 (5), which shows that these deposits constitute about 40% of the area.

Typically, the Fraser Delta deposits have the following structure of layers:

1) a surficial deposit comprised of thin layers of clays, silts and peats (max. thickness of 8 m);
2) sand deposits (max. thickness 45 m);
3) silt-clay deposits (max. thickness 200 m);
4) glacial deposits (max. thickness 100 m);
5) bedrock

The water table in the lower areas is generally within a metre of the ground surface.

The western portion of the Greater Vancouver Area except the central hilly part of the municipality of Surrey is generally underlain by silty-clay deposits, while there are peat deposits in the eastern portion. The liquefaction threat is mainly for thick layers of sand deposits underlying a thin crust of surficial deposits of clays or silts. The dynamic liquefaction resistance of these sands can be estimated from their standard penetration resistance value N. A preliminary assessment of liquefaction potential will be discussed in the Section 4.4 of this report.

4.3 Conditions for Liquefaction During Earthquakes

From a practical point of view, liquefaction will occur when the induced dynamic stress exceeds the dynamic strength of the soil. The dynamic stress is a function of the earthquake magnitude, epicentral distance as well as the geometry and mechanical properties of the soil deposit. On the other hand, the dynamic strength is a function of the soil type and the duration of shaking. There are a number of methods of expressing the dynamic stress and the dynamic strength. The method presented by Seed et al. (11), which contains the essential concepts, has been widely used and is discussed herein.

Based on this method, the dynamic stress, τ_h is given by:

$$\tau_h = 0.65 \frac{a_{max}}{g} \sigma_v r_d \quad (1)$$

where a_{max} = peak horizontal acceleration at ground surface
g = gravitational acceleration
σ_v = total vertical stress
r_d = a reduction factor with depth.

The value of a_{max} depends on a number of factors including the spectrum of earthquake waves, attenuation property of the bedrock, and the amplification due to the soil deposit.

The dynamic strength (τ_l) was established by Seed et al. (11) based on observations of actual earthquakes around the world. It is expressed in terms of the Normalized Standard Penetration Test (SPT) resistance (N_1) and a coefficient (μ) related to earthquake magnitude. A general form of the expression can be given by:

$$\tau_l = \mu f(N_1) \quad (2)$$

where $f(N_1)$ is a function of N_1. There are different functions for sand and for silty sand.

Liquefaction will take place when the dynamic stress (τ_l) exceeds the dynamic strength (τ_h):

$$\tau_l/\tau_h \leq 1.0 \quad (3)$$

4.4 Liquefaction Potential in the Greater Vancouver Area

Liquefaction potentials for two different earthquake conditions are assessed for the alluvial deposits in the Greater Vancouver area. The first is based on the design earthquake NBCC 1985, with a return period of 475 years and a peak bedrock acceleration (a_m) of 0.20 g. The corresponding design earthquake magnitude (M) as suggested by Byrne and Anderson (6) is taken as 7.0. The second is based on a "major earthquake" with a_m = 0.5 g and M8.5.

The induced dynamic stress (τ_h) depends on the maximum ground surface peak acceleration (a_{max}) which is a function of the bedrock acceleration a_m. A study by Byrne and Anderson (6) on typical soil profiles from Richmond shows that either slight amplification or deamplification is possible when the seismic waves travel from bedrock through the soil to ground surface. Here it is assumed, therefore, that there is no change in amplitude of the acceleration from bedrock to the ground surface, i.e., $a_{max} = a_m$.

The dynamic strength of the alluvial deposit can be obtained from the Standard Penetration Test SPT. Figure 5 shows profiles of regular SPT resistance (N) at various sites in Richmond and the Fraser Delta (12). N can be normalized by the confining pressure to yield N_1 for application in Equation (2).

Some soil variability can be clearly identified and, therefore, in order to assess accurately the dynamic strength, each site has to be studied separately. It is however, revealing to consider some typical profiles to give a broad picture of the liquefaction potential for this region. Three profiles are chosen for this purpose: the mean, the lower bound and the upper bound. These profiles are obtained from the information shown in Figure 5. The mean corresponds to the average of all the profiles while the lower and upper bounds correspond to the weakest and strongest profiles. From these profiles, the dynamic strengths are obtained using Equation (2). Since both sand and silty sand exist in this region, strength profiles for both soil types have been obtained.

The liquefaction potential of the deposits from the Fraser Delta can now be studied by comparing the dynamic strength (τ_l) and dynamic stress (τ_h). The results are shown in Figure 6 and Figure 7. Figure 6 shows for the design earthquake that sand and silty sand with average strengths are expected to liquefy to depths of 8 m and 5 m, respectively. Figure 7 shows for the "major earthquake", that all sand and silty sand layers with average strengths will liquefy. Even if the sand and the silty sand layers possess the upper bound strengths, they are expected to liquefy to depths of 16 m and 9.5 m, respectively. Thus liquefaction and the associated damages will occur at some locations for the design earthquake, but will be extensive for the "major earthquake".

4.5 Hazard Map and Land Use Maps

With the past and ongoing construction activities in the greater Vancouver area, it is conceivable that a lot of soil information now exists. This information can be collected and processed with regard to liquefaction potential and other possible associated types of hazards. Hence, maps can be compiled for evaluating the safety of existing buildings and for future development. Furthermore, land use maps can be developed for use by regulatory bodies to maximize the appropriate exploitation of land. They can also be an extremely valuable documents for reconstruction decisions following a major earthquake disaster.

5. DAMAGE POTENTIAL

5.1 Impact of Earthquake on Residential Structures

The impact of major earthquakes is evaluated based on the available data from past well-documented events. The most important is the San Fernando earthquake of February 9, 1971 of magnitude M6.6 on the Richter scale, (13, 14, 15) and the Alaska earthquake (20,21). Reference is also made to some events which were generated in the Juan de Fuca subduction zone (the Puget Sound earthquake of April 29, 1965 with M6.5, the Olympia earthquake of April 12, 1949 with M7.1) in the state of Washington (7). There are four types of structures considered and they are grouped in the following scheme:

- single family houses of wood frame constructions, one or two storeys;
- low and medium-rise buildings include
  - low-rise buildings 2 to 4 story residential buildings or various small buildings like banks, and small shopping areas;
  - medium-rise buildings 5 to 9 story residential and office buildings;
- high-rise buildings include high-rise residential and office building > 10 storeys;

- schools and hospitals include buildings of special importance in the endangered area. They could vary in size and height, but in general schools are of bearing wall type and hospitals are reinforced-concrete frame structures up to about 10 storeys.

The Greater Vancouver Area is a typical North American urban, heavily populated area with clearly distinguished residential, down-town, industrial and harbour zones (Fig. 8).

Several important standards regarding an evaluation of the seismic resistance of existing buildings (16) and also investigation procedures of the correlation between earthquake ground motion and building performance (17,18) were published by the Applied Technology Council (ATC) in the USA.

An extensive study of earthquake damage evaluation data for California was performed by ATC between 1982-1985 (19). The study was designed to develop earthquake damage evaluation data for facilities in California and was focussed on estimating the economic impacts of a major California earthquake on the state, region and nation.

The ATC divides all buildings into six categories with regard to the dominant structural material (13):

I	Wood buildings
II	Steel buildings
III	Cast-in-place reinforced concrete buildings
IV	Buildings with precast concrete elements
V	Reinforced masonry buildings
VI	Unreinforced masonry buildings

Refs. 17 and 18 present procedures to be followed in determining building performance for model building types, but are applicable only for very detailed studies. A simplified prediction of the earthquake performance will be discussed here.

5.1.1 Single-family Houses

Single family houses include all detached or semi-detached houses, townhouses and other small size dwelling houses. Essentially all of the houses in the Greater Vancouver Area including two- and three-story apartment complexes and condominiums are simple wood frame construction and belong to the category I - Wood Buildings. Some single family houses of the older type belong to category VI - Unreinforced Masonry Buildings. A combination of these two categories is also possible. Most of the residences are predominantly one-storey structures, although some are two-storey.

The San Fernando earthquake of February 9, 1871, a shallow type earthquake of magnitude M6.6 on the Richter scale, was perceptible over approximately 80,000 square miles of California, Nevada and California. The maximum intensity IX to XI on the Modified Mercalli Scale was confined to relatively small areas in the foothills of the northeastern corner of the San Fernando Valley (13). The zone of intensity VIII was approximately 1000 sq. miles. In both zones, the ground accelerations reached about 0.30g. Many of the split-level residences collapsed or partially collapsed. Many of unreinforced masonry residential buildings were heavily damaged or collapsed. Many collapses were due to wide openings like garage doors, which offered little lateral resistance. Masonry chimneys on many residences collapsed completely even during relatively moderate earthquakes (Puget Sound of April 79, 1965, Olympia of April 13, 1949) (7).

Similar damage patterns could be expected in a "design earthquake" in Vancouver since 0.3g corresponds to the design value for the Greater Vancouver Area for 1000 year return period, but the

design earthquake will have a longer duration of shaking (> 3 min). About 2-5% of the low-rise buildings would be expected to suffer major damage.

For a "major" earthquake with accelerations reading 0.5g or higher, most of the buildings of category VI - Unreinforced Masonry Buildings will be heavily damaged or will collapse and be uninhabitable. Also, many of split-level residential houses or other houses with irregularities and of mixed structural type will collapse. About 10 to 30% of all single storey houses in the Vancouver area are expected to suffer major damage.

The damage will be associated not only with ground shaking, but also with slides on the water front areas and differential settlements of ground due to the liquefaction of loose sand deposits such as in the Fraser Delta.

5.1.2 Low and Medium-rise Buildings

About 20% of all residential buildings are low-rise apartment buildings in the 2 to 4 storey range and some various types of small buildings like banks, retail structures or small warehouses (1 to 2 storey) may be also included in this category.

The minor, and in some cases major, structural damage, especially to connections, was experienced for this type of building during the San Fernando earthquake (13) and also during the Alaska earthquake of March 27, 1964 (20,21). However, the Alaska earthquake of 1964 was accompanied by massive landslides in coastal areas. These landslides were caused by sudden changes of tectonic structure and tsunami waves reaching a height of 10 m, which are unlikely to occur in the Vancouver area. The magnitude can be very similar, however, and may range from M8 to M9 on the Richter scale. Earthquake induced submarine slides can also be very dangerous for low and medium-rise buildings in the harbour and other coastal areas.

For a "major earthquake" with an epicenter 100 km from the Vancouver area, the estimated damage to low-rise buildings will depend on local ground conditions and on occurrence of fissures and cracks on the ground surface. Severe shaking may be experienced, which would lead to heavy damage for structures that have lower stiffness of ground level stories or big openings. An estimated 60% of all low-rise residential and office buildings may experience major or minor damage, depending on local ground conditions. An estimated 20-30% of these buildings are likely to be temporarily uninhabitable.

Medium-rise buildings include 5 to 9 storey residential buildings or various office buildings, including medium size motels and hotels. These buildings belong to ATC categories II, III, IV or V listed at the beginning of this section.

The typical earthquake motion on rock or firm ground has a low predominant period in the range of 0.1 to 0.5 seconds. The medium-rise buildings on firm ground or rock may experience severe shaking during a design earthquake and, due to their low fundamental periods of vibration (0.3 to 1 sec), response can be magnified due to resonance. Severe structural damage can be experienced for these structures. Total collapse will be rare, but can take place for resonance cases of the reinforced concrete buildings having limited ductility of columns on one of the lower stories.

During the San Fernando earthquake of 1971, some well-instrumented structures experienced rather high horizontal accelerations, up to 0.4 g, and vertical accelerations up to 0.25 g (e.g. Holiday Inn Hotel, Orion Ave., located about 20 km from the epicentre). These structures performed well with only minor cracking of structural components of the structure. However, architectural damage was seen everywhere (14).

For the Vancouver area it is estimated that about 20-30% of medium-rise structures can experience minor structural damage during an NBC design earthquake and most of these buildings will remain habitable. However, the architectural damage (falling fixtures, partition walls and small architectural elements on ceilings) can be substantial, and damage to block partitions, windows and big glass walls can be very dangerous for inhabitants. Some of these buildings may need to be evacuated due to extensive architectural damage.

Most of the low and medium-rise buildings are founded on sand fill up to 1 metre thick and their foundations were preloaded. Some of these structures are also founded on piles (e.g. Franki piles). The liquefaction hazard will be reduced by sand fills and preloading, and soil failure may not occur. Damage due to differential settlement may occur, especially when buildings cross a ground fissure. Buildings with reinforced slab construction could experience moderate damage due to differential settlement.

5.1.3 High-rise Buildings

The Greater Vancouver Area has several locations with high density of the high-rise residential buildings, especially in the downtown city core and in the West End and water front areas. These buildings can create a major risk due to cumulative damage or collapse as was experienced, for example, in the Mexico City 1985 earthquake (22). The overall response of these buildings will depend on many factors and some of them are very difficult to evaluate a priori. Some of the main factors are the type of foundation used for the structure and the local ground conditions. Two potential hazardous areas include the Fraser Delta and the water front especially on banks of the English Bay and Burrard Inlet. Both of them show poor ground conditions with alluvial type of deposits and silty sands that are prone to liquefaction.

The percentage of high-rise buildings collapsed or severely damaged during the Mexican earthquake of 1985 was very high (16% in range 6-8 story, 25% in range 9-12 story and 22% for > 12 storey), in total, about 3500 buildings. The seismic waves that were transmitted through firm ground had dominant periods which were amplified by the soft soil strata resulting in a large number of cycles of ground motion with a period of about 2 seconds (22). A similar amplification and shift in predominant period was also reported during the Caracas, Venezuela earthquake of 1967 (magnitude M 6.5), when many buildings (>10 storey) were heavily damaged, but only four collapsed completely (23). Better ground conditions and good design resulted in a very few severely damaged high-rise structures during the 1985 Chile earthquake of magnitude M 7.8 (24). The Managua, Nicaragua earthquake of 1972 of magnitude M 6.2, resulted in 10,000 people killed mainly due to the collapse of small houses of native taquezal constructions, but most of high-rise reinforced concrete structures designed according to up-to-date standards had escaped with minor or little structural damage (25). Very good performance of high-rise buildings was exhibited during the 1971 San Fernando earthquake including the 32-story Bunker Hill Tower located about 42 km south from the epicentre and with ground accelerations 0.2g - 0.4g. All of these Californian buildings were designed according to the Californian code (SEAOC).

During the 1964 Anchorage, Alaska earthquake of magnitude M8.4, the damage was greater to multi-storey long-period buildings than to one- and two-storey short-period buildings. A typical pattern for damage was the shear-cracking of the spandrel beams for the 14-story reinforced concrete structure of the 1200 L Street Apartment Building. The structure, however, did not collapse and remained habitable (21).

From the above summary of different damage to high-rise buildings during past events, some conclusions may be drawn for a predicted "design" and "major" event in the Vancouver area.

Buildings which have been designed according to present codes are much safer than those designed to previous codes and only minor structural damage should occur in a "design" earthquake. Nevertheless, high-rise frame structures with precast cladding and in-filled walls of unreinforced masonry are at greater risk than shear wall or braced structures. Of higher risk from the damage point of view are

high-rise structures designed and constructed before 1970. Heavy structural damage may be experienced in case of these structures, but the overall percentage of the buildings which could collapse completely is expected to be less than for the Mexican 1985 earthquake (20%-25% total collapse). A number of high-rise buildings in the Greater Vancouver Area are supported on piles. The effect of liquefaction of the ground in the vicinity of the piles could lead to foundation failure from sinking and buckling of piles and consequent severe structural damage.

High-rise buildings designed to the NBC earthquake would be exposed to more severe conditions during a "major earthquake" (0.5g). The predicted long duration of 3-5 minutes can be very dangerous for these structures and can lead to cumulative damage after each cycle of vibration and eventually cause total collapse. The percentage of high-rise buildings severely damaged or destroyed can be estimated to be about 15%-20% and could vary substantially from one location to another in the Vancouver area due to the local ground conditions, date of construction, and properties of the building.

5.1.4 Schools and Hospitals

Schools and hospitals, essential for post disaster services, should have a high quality design and construction. They are required to be designed to higher seismic loads than other buildings in recent decades.

Many schools have a simple wood frame construction and the floor is usually a concrete slab on grade. Schools often have recreational facilities within their grounds. Unreinforced brick or concrete block walls are often used in corridors, in gymnasium areas etc. Some contemporary school designs have big openings and windows and have a complicated structural configuration. Other schools are one- and two-storey concrete bearing wall structures with interior corridors. Some are of steel frame construction. Still others, older ones, are of unreinforced masonry. Schools therefore include all categories of structures.

During the Long Beach-Compton earthquake of March 11, 1933 of magnitude M6.3 most schools and school recreational areas were heavily damaged. Fortunately, the earthquake occurred in the evening, after school hours. Most of these schools were later demolished and rebuilt. Prompt action by the California legislature led to adoption of a new law (the Field Act) to regulate construction and design requirements for schools. During the San Fernando earthquake in 1971, several schools were damaged, but most of them withstood this earthquake. Only schools built before the Field Act (1933) showed substantial damage and some were later demolished. School buildings constructed prior to 1933 that were reinforced to resist earthquake forces escaped the earthquake with minor damage. Altogether there were 200 public schools within the area subjected to strong ground motion (0.20g - 0.45g) and at least 25 were within one mile of the zone of ground rupture. Only one modern school located on the fault experienced severe structural damage (substantial cracks and differential settlement). In contrast, 13 older (pre-Field Act) buildings were seriously damaged; 10 were demolished later (13,14).

The above comments illustrate the importance and benefits of proper design of school buildings.

An estimate of the damage to schools in the Greater Vancouver Area is difficult due to the variety of structures used and their different construction times. Also, a rehabilitation program has been initiated for older schools. However, it is estimated that in a "major earthquake" about 10%-20% of newer school buildings can be damaged so as to make them uninhabitable.

Even greater importance must be assigned to the structural performance of hospital buildings during an earthquake. The San Fernando earthquake of 1971 provided the following damage to hospitals: it heavily damaged the 850-bed Los Angeles Olive View Medical Center; heavily damaged the 420-bed San Fernando Veteran's Administration Hospital - 2 major buildings collapsed; damaged Holy Cross Hospital. The collapse of 2 major buildings of San Fernando Veteran's Administration Hospital led

to heavy loss of life. These buildings were constructed between 1925-1927 and consisted of reinforced concrete structural frames with unreinforced clay tile exterior walls. They were not designed to resist seismic forces because no recognized standard for this purpose was in use at that time (13,14,15). The main buildings of two other hospitals of modern reinforced-concrete design (slab-column structures with shear walls) experienced heavy damage, but did not collapse. In case of the Olive View Medical Center the first two stories were shifted by 15 in.; the tied columns failed completely, but spiral columns showed tremendous amount of ductile capacity, which prevented the total collapse of the structure.

It is difficult to estimate the damage to hospitals in the Greater Vancouver Area. Old hospitals with unreinforced masonry walls would be heavily damaged in a "design earthquake" and a few could collapse. During a "major earthquake" with accelerations about 0.5g, many older hospital buildings could collapse. Many modern hospitals could experience heavy architectural damage, and some may have to be evacuated. The final effect could be a serious disruption of medical services (including emergency services) for the metropolitan area of Vancouver and adjacent municipalities. It can be assumed that in a "major earthquake" about 20%-40% of old hospital buildings may collapse and up to 60% may be heavily damaged depending on their location and the specific structural characteristics.

5.2 Impact of Earthquakes on Services

Every city has its own services or lifelines that enable the supply and flow of people, goods, information, energy (power and gas), and water by means of transportation, the system of communication, and energy and water systems. In general, a lifeline is a network within which there are sources, major transmission lines, storage, and a distribution or collection system. Each type of lifeline has its own designed and operational characteristics and also its own vulnerability to earthquakes (26). In this section an estimate of damage to lifelines in the Vancouver area is presented.

5.2.1 Surface Transportation - Road and Bridges

Deficiencies of earthquake resistant design relative to city lifelines were shown during the 1971 San Fernando earthquake. Post-earthquake reports to the California State Highway Commission indicated that the earthquake damaged 11 miles of freeways and 6 miles of conventional state highways, in addition to numerous city and county streets. About 60 bridges experienced from little to major damage; 6 collapsed completely or were damaged to such extent that they needed to be removed and replaced at great cost (13).

The surface transportation network in the Greater Vancouver Area includes roads and freeways with a number of bridges connecting the banks of the Fraser River and across various inlets. The system of interchanges and highways is far smaller than in the San Fernando Valley and in the City of Los Angeles. However, the predicted "major earthquake" will have a higher intensity and higher ground accelerations (>0.5g) than those experienced during the 1971 San Fernando earthquake. Thus, the severe ground shaking can destroy bridge columns and abutments. Localized landslides may occur in earth filled areas. About 20-40% of all bridges can be heavily damaged or will collapse and will be effectively unusable. The rupture of the road surfaces together with uplifts of similar scale to the 1964 Alaska earthquake can leave many roads closed to any form of traffic. The George Massey Tunnel in Richmond may be heavily damaged due to liquefaction of sand beneath and sand backfill at the sides of the tunnel.

The differential movements and rupture of ground can also stop rail movement due to bent rails. Large settlements of fills and looser sands may occur, especially in the Fraser Delta region.

5.2.2 Energy, Water and Gas Lines

Piping systems of any kind are very vulnerable to damage during even moderate earthquakes. Heavy damages for energy, water and gas lines were reported during the 1971 San Fernando earthquake (M6.6), the 1949 Olympia earthquake (M7.1) and the 1965 Puget Sound earthquake (M6.5) (7,13,14). Energy, water and gas supplies were broken.

For a "major earthquake" in the Greater Vancouver Area all underground piping systems may be affected. Lines located on the surface are very vulnerable to ground rupture and cracking, uplifts and heavy shaking. Power transmission lines can be damaged in some areas and power cuts will be common. Transformers may be shifted and some can be heavily damaged. Broken gas lines can cause local fires, which can be difficult to control during a major disaster due to a shortage of water. The predicted worst scenario for the Vancouver Area can lead to the total failure of energy, water and gas line supplies and it may leave more than 60% of the area without power and water. An underground jet fuel line leading to the airport would also be subject to rupture as a result of differential ground movement and possible liquefaction.

5.2.3 Public Utility Structures, (Dykes, Dams, etc.)

Public utility structures include dykes, dams, sewage system structures and other structures which are essential for every community. During the 1925 Santa Barbara earthquake, the Sheffield Dam failed completely, but did not cause deaths or major downstream damage (22). Some damage to other earth or concrete gravity dams during earthquakes was reported in the literature (7). The Lower San Fernando Dam in San Fernando was severely damaged, but flooding of downstream areas was avoided (14,15).

Some damage to the sewage system can be anticipated and damage to the sewage treatment plants can be significant. The sewer lines are usually buried 1 to 3 metres below the ground surface and can suffer substantial damage and leakage due to differential settlement as a result of landslides or soil liquefaction.

The Fraser Delta region is ringed with a number of low dykes to prevent flooding during high tides. The dykes are generally 4 to 6 metres in height with side slopes of about 3 horizontal to 1 vertical and comprised of silty sand. The probability of high tide occurring coincident with a "major earthquake" is remote, but cannot be completely ruled out. Liquefaction of soils at the base of the dyke may occur, which would result in a break. Tsunami waves are not a likely possibility in this area since the relatively narrow Strait of Juan de Fuca acts as a barrier to tsunamis originating in the Pacific Ocean (Fig. 1).

There are a number of dams belonging to the B.C. Hydro in the surrounding valleys near the Greater Vancouver Area. A dam failure can result in a major disaster and cause heavy flooding especially in the Fraser Delta region. The Capilano Dam in North Vancouver controls the drinking water reservoir for the area and a failure would be disastrous. However, more specific studies are required in this matter. Some of these studies may already have been carried out by the respective owners of the dams.

5.2.4 Industrial Structures (including Storage Tanks, Harbour Facilities, etc.)

Industrial buildings, conveyors, cranes and storage tanks are mostly steel framed light structures. Industrial halls are not likely to experience much structural damage, but other structures mentioned can be moderately damaged and, in some cases, would collapse.

Waterfront facilities, like harbours may be heavily damaged not only due to severe shaking, but also to local slides. Severe damage was experienced to harbour facilities during the 1964 Anchorage, Alaska earthquake (20,21). During a "major earthquake" in the Vancouver area approximately 40% of all harbour facilities may be heavily damaged. The damaged facilities would include docks, piers, cranes and other types of industrial structures. Some are likely to be located in areas prone to submarine slides or soil liquefaction.

5.2.5 Runways and Airport Facilities

Vancouver International Airport is located on Sea Island. The airport terminal is a 3 story building founded on a deep fill that was heavily preloaded prior to construction (6). Liquefaction beneath the terminal is unlikely to occur during the design earthquake. However, some liquefaction may take place under adjoining elevated walkways and can cause differential settlement of these structures. Liquefaction beneath the runways could also occur, resulting in extensive cracks and making the airport facilities unusable.

For a "major earthquake", liquefaction will result in sand boils, uneven settlement and ground surface cracking. The airport terminal could be damaged as well, and runways will be heavily damaged as occurred at Niigata airport during the Niigata earthquake in 1964. Thus, the airport facilities will be shut down.

5.2.6 Communication Systems (Airport, Police, Radio and TV, Telephone, etc.)

An earthquake can severely damage and disable communication systems and limit the efforts to respond to casualties and destruction in an affected area.

During a predicted "major earthquake" in the Vancouver Area the airport, police, radio and TV communication systems can be affected depending on the locations of these facilities. The Vancouver International Airport location on Sea Island is prone to heavy liquefaction and a disruption of all communication services might result from severe shaking of equipment.

Most telephone networks are located above ground and supported on timber poles, for which damage is expected to be slight when located on firm ground. Liquefaction of loose sands, however, can cause them to sink or tip. For newer services with underground cable networks, severe damage to buried cables can be expected to disrupt the telephone communication system in the whole area.

It is evident that all of these systems must have an emergency backup.

6. SUMMARY OF ESTIMATED MAJOR STRUCTURAL DAMAGE

In this section a summary of estimated major structural damage in the Greater Vancouver Area is presented in Table 2. Major structural damage implies that the residential building structure is damaged to such extent that substantial repairs are needed before occupants can return; the earthquake damage presents a safety hazard or in extreme cases requires demolition of the building. The estimates exclude architectural damage to glass walls, windows, partition blocks, architectural ceilings or lighting fixtures, which may also lead to temporarily closure of specific residential and other facilities. The presented percentage losses for both the "design earthquake" and "major subduction earthquake" are not based on a statistical analysis, but represent best estimates by the authors. For a reliable statistical analysis, future full scale study of similar scope to one performed for the State of California may be required (19).

Table 2: Summary of Estimated Major Structural Damage

	Design Earthquake (NBCC 1985)	Major Subduction Earthquake
Probability of Occurrence:	0.0021	
(per annum)	475	600-1000
(return period, years)	0.20 g	0.50
Peak Ground Acceleration:		
Type of Building or Service	**Estimated Loss Ratio, %**	**Estimated Loss Ratio, %**
Single family houses of wood frame construction	2-5	10-30
Unreinforced masonry	20-50	50-100
Low and medium rise residential and office	5-10	20-30
High-rise residential	5-10	10-20
Schools and hospitals:		
old construction <1940 (not strengthened)	10-30	30-60
newer construction	2-5	10-20
Gas and water supply, sewers	5-10	40-60
Electricity	5-10	20-50
Communication systems	10-20	20-40
Transportation routes (bridges)	5-10	20-30
Harbour facilities	5-20	40-50
Airport structures	2-5	10-20
runways	5-20	40-70

7. EFFECTS OF MAJOR STRUCTURAL DAMAGE

7.1 Safety and Health

Earthquake-related deaths and serious injuries can be caused by:

- Collapse due to shaking
  - collapse of whole building (e.g. unreinforced masonry)
  - partitions and glass
  - cladding and parapets
- Landslide destroying or covering buildings
- Sudden flood
- Fire in high rise buildings
- Explosion
- Driving into gaps missing in roads or collapsed bridges
- Live electric wires

It is difficult to estimate incidence of deaths and serious injuries in the Vancouver area without investigating these potential hazards more carefully. A review of a similar investigation in California (19) indicates an estimate of 5 to 50 deaths per million for a design earthquake and 50-500 deaths per million for a "major earthquake", with similar estimates for serious injuries, i.e. those for which full recovery does not occur.

Health issues are also difficult to estimate without further study. Such issues include:

- lack of adequate health care facilities and transportation
- unclean water and sewage back-up
- psychological effects during and after a disaster.

7.2 Fire

Fires usually occur after destructive earthquakes. In earlier times they were uncontrolled (San Francisco 1906, Tokyo 1923) and resulted in terrible loss, including many lives (7). In recent times this has not occurred. Factors affecting uncontrolled fires have been loss of water (due to ground failure, especially near the water source), combustible construction without sufficient separation, too many fires to control and difficulty of access.

The combined circumstances leading to uncontrolled fire do not appear to occur in the Vancouver area, but this needs to be looked at more carefully. In particular, are safety mechanisms in gas and electricity systems adequate to minimize fire ignition? For example, 109 fires occurred following the San Fernando earthquake in 1971. Is there sufficient separation of wood houses which, when combined with likely wind conditions, makes rapid fire spread unlikely?

Fires in high-rise buildings can start due to electrical equipment failure in mechanical floors and would endanger inhabitants above. If the earthquake damages fire barriers such as block walls and entrances to stairwells the problem becomes very serious. Potential damage to high-rise buildings, therefore, needs attention for this combined hazard.

7.3 Rehousing

Since the area of destruction in a "major earthquake" can cover large sections of a city, rehousing the population that is evacuated from severely damaged buildings becomes a major problem. It is currently assumed that schools would serve as emergency shelter, both the gymnasium and the classroom areas. Schools are currently designed to higher seismic forces and they should therefore suffer less damage than other comparable buildings.

Should schools suffer major damage, however, or be unable to cope with the demand for shelter, temporary structures would be needed. These can include tents, fabric structures (self-supporting or air supported), or trailers. Transporting these to required locations might be difficult since transportation routes may also be severely affected. The armed forces could provide valuable assistance in such circumstances.

Special problems are encountered when large numbers of injured need to be cared for. Should hospitals be damaged, not only are they unable to accept new patients, but the current patients would need to be evacuated.

These are some of the reasons why the availability of schools and hospitals for post-disaster service should be verified and assured.

8. TOPICS THAT NEED FURTHER STUDY

This assessment of earthquake effects on the Greater Vancouver Area revealed a number of aspects which need further investigation. The topics are listed sequentially, without any priority rating.

- Improve the knowledge of quantitative engineering properties of the subduction earthquake (e.g. location, magnitude, recurrence intervals, and ground motion characteristics).
- Establish detailed maps showing the hazards of landslides, soil liquefaction, ground motion amplification and flooding as a result of seismic activity.
- Perform a detailed study of seismic performance of representative types of buildings (low rise, medium, high rise) and soil deposits in the Greater Vancouver Area. Some soil studies for the Fraser Delta area are already available.
- Establish an evaluation procedure to determine the need for seismic rehabilitation of buildings. This should utilize California experience and that of other countries (e.g. New Zealand, Japan).

9. REFERENCES

1. Weichert, D.H., Munro, P.S. - "Canadian Strong Motion Seismograph Networks", Proceeding of the 5th Canadian Conference on Earthquake Engineering, Ottawa, pp. 647-654, 1987.

2. Heaton, T.H., Kanamori, H. - "Seismic Potential Associated with Subduction in the Northwestern United States", Bulletin of the Seismological Society of America, Vol. 74, No. 4, pp. 933-941, June 1984.

3. Milne, W.G., Rogers, G.C., Riddihough, R.P., McMechan, G.A., Hyndman, R.D., - "Seismicity in Western Canada", Canadian Journal of Earth Sciences, Vol. 15, pp. 1170-1193, 1978.

4. Rogers, G.C., - "An Assessment of the Megathrust Earthquake Potential of the Cascadia Subduction Zone", Canadian Journal of Earth Sciences, Vol. 25, pp. 844-852, 1988.

5. Blunden, R.H. - "Urban Geology of Richmond, B.C.", University of British Columbia, Department of Geology, Report 15, 1973.

6. Byrne, P.M., Anderson, D.L. - "Earthquake Design in Richmond, British Columbia", A report prepared for Corporation of the Township of Richmond, B.C., Dept. of Civil Engineering, University of British Columbia, Vancouver, B.C., 1987.

7. Wiegel, R.L.(editor) - "Earthquake Engineering", Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.

8. Borg, S.F. - "Earthquake Engineering - Mechanism, Damage Assessment and Structural Design", Second and Revised Edition, World Scientific Publishing Co. Rte. Ltd., Singapore, 1988.

9. National Building Code of Canada (NBCC), National Research Council of Canada, Ottawa, 1985.

10. Rogers, G.-A. - "Documentation of Soil Failure During the British Columbia Earthquake of 23 June, 1946", Canadian Geotechnical Journal, Vol. 17, No. 1, pp. 122-127, 1980.

11. Seed, H.B., Idriss, I.M., Arango, I. - "Evaluation of Liquefaction Potential Using Field Performance Data", J. of Geotechnical Engineering Division, ASCE, Vol. 109, No. 3, pp. 458-482, 1983.

12. Wallis, D.M. - "Ground Surface Motions in the Fraser Delta Due to Earthquakes", M.A.Sc. Thesis submitted to the University of British

13. Lew, H.S., Leyendecker, E.V., Dikkers, R.D. - "Engineering Aspects of the 1971 San Fernando Earthquake", Building Science Series 40, National Bureau of Standards, Washington, D.C., 1971.

14. "San Fernando, California Earthquake of February 9, 1971", in three volumes, U.S. Department of Commerce, National Oceanic and Atmospheric Administration and Earthquake Engineering Research Institute, Washington, D.C., 1971 (Volume I - Effects on Building Structures, Volume II - Utilities, Transportation, and Sociological Aspects, Volume III - Geological and Geophysical Studies).

15. "The San Fernando, California, Earthquake of February 9, 1971", a Preliminary Report Published Jointly by the U.S. Geological Survey and the National Oceanic and Atmospheric Administration, Geological Survey Professional Paper 733, Washington, D.C., 1971.

16. ATC-14 - "Evaluating the Seismic Resistance of Existing Buildings", Report of the Applied Technology Council, California, 1987.

17. ATC-10 - "An Investigation of the Correlation Between Earthquake Ground Motion and Building Performance", Report of the Applied Technology Council, California, 1982.

18. ATC-10-1 - "Critical Aspects of Ground Motion and Building Damage Potential", Report of the Applied Technology Council, California, 1984.

19. ATC-13 - "Earthquake Damage Evaluation Data for California", Report of the Applied Technology Council, California, 1985.

20. "After Action Report - Alaska Good Friday Earthquake", 27 March 1964 prepared for U.S. Army Engineer Division, North Pacific by Alaska District, January 1968.

21. "The Great Alaska Earthquake of 1964 - Engineering", Committee on the Alaska Earthquake of the Division of Earth Sciences, National Research Council, National Academy of Sciences, Washington, D.C., 1973.

22. Mitchell, D., Adams, J. DeVall, R.H., Lo, R.C., Weichert, D. - "The 1985 Mexican Earthquake - A Site-Visit Report", Seismological Service of Canada, Earth Physics Branch, Energy, Mines and Resources, Canada, Ottawa, 1986.

23. Hanson, R.D., Degenkolb, H.J. - "The Venezuela Earthquake, July 19, 1967", American Iron and Steel Institute, New York, 1969.

24. Ridell, R., Wood, S.L., de la Llera, J.C., - "The 1985 Chile Earthquake - Structural Characteristics and Damage Statistics for the Building Inventory in Vina del Mar", a Report to the National Science Foundation, University of Illinois at Urbana-Champaign, Urbana, Illinois, 1987.

25. Wyllie, L.A., Wright, R.N., Sozen, M.A., Degenkolb, H.J., Steinbrugge, K.V., Kramer, S., - "Effects on Structures of the Managua Earthquake of December 23, 1972", Bulletin of the Seismological Society of America, Vol. 64, No. 4, pp. 1069-1133, 1974.

26. "Earthquake Prediction and Public Policy", Report prepared by the Panel on the Public Policy Implications of Earthquake Prediction of the Advisory Committee on Emergency Planning, Commission on Sociotechnical Systems, National Research Council, National Academy of Sciences, Washington, D.C., 1975.

APPENDIX 1

Modified Mercalli Intensity Scale (1931)
(Ref. 7)

Intensity	Description	Average Peak Acceleration ($g = 9.80\ m/s^2$)
I.	Not felt except by a few under especially favorable circumstances	
II.	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	
III.	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing truck.	
IV.	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.	0.015g - 0.02g
V.	Felt by nearly everyone, many awakened. Some dishes, windows, etc. broken, cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	0.03g - 0.04g
VI.	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight.	0.06g - 0.07g
VII.	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.	0.10g - 0.15g

VIII.	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; damage great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed.	0.25g - 0.30g
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	0.50g - 0.55g
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks.	More than 0.60g
XI.	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.	
XII.	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.	

APPENDIX 2

List of Keywords Associated with Earthquake Engineering

Architectural damage	superficial type of damage not affecting load carrying capacity of a given structure (e.g. hairline cracks, spalling, breaking of glass windows, etc.).
Cumulative damage	the result of not only the main shock but also several aftershocks.
Differential settlement	uneven settlement of different parts of the foundation of the structure usually caused by poor soil conditions. During an earthquake, can be caused also by liquefaction of soil deposits or a sudden change of the surface of the ground (cracks etc.).
Epicentre	the point at the earth's surface directly above the focus (hypocentre) of an earthquake.
Fault	the plane along which movements have occurred in the earth's crust (e.g. St. Andrea's fault in California). Some are active and generate earthquakes and some are inactive at the present time.
Focal point	focus (hypocentre) of an earthquake. Earthquakes may be classified according to depth of focus: shallow: within 70 km of earth surface intermediate: 70-300 km deep: beyond 300 km
Ground motion amplification	a phenomenon which takes place when seismic waves become larger when they travel vertically from rock through soil deposits.
Hypocentre	the focus or origin of the earthquake within the earth's crust.
Isoseismical map	the map which shows the geographical distribution of damage. Isoseismal lines separate one group of equal intensities from another.
Liquefaction	a process in which soft loose soil deposit (e.g. sand, silty sand) is being transformed to a liquid as a result of earthquake shaking or by other dynamic disturbance.
Long-period buildings	have fundamental period of free vibration in the range 1-2 seconds or more. These are generally tall buildings.
Short-period buildings	have fundamental period of free vibration in the range 0.1-0.5 seconds. These are generally buildings with only a few storeys.

Modified Mercalli Intensity Scale	a descriptive scale, indicating damage or the effects on humans corresponding to different intensities of shaking from earthquakes (Appendix 1)
Peak Horizontal Acceleration (PHA, g)	maximum acceleration amplitude of horizontal ground motion expressed as a ratio of normal ground acceleration (g).
Peak Horizontal Velocity (PVA, m/s)	maximum velocity amplitude of horizontal ground motion, measured in m/s.
Plate (platelette)	a geological term referring to the major portions of the earth's crust. Movement occurs along these plate boundaries.
Predominant period of ground motion	the major repetitive component of ground motion at a certain period of vibration.
Probability of exceedence (P)	probability that an earthquake will exceed a certain level, based on a statistical analysis of the earthquakes that have been experienced or can be expected in a given region.
Return period (1/P, years)	the average number of years between two probable earthquake events in a given region. It can be calculated as the inverse of the probability of exceedence.
Richter Magnitude Scale	the earthquake magnitude scale developed by C.F. Richter in 1935, which is a measure of the total energy release of the earthquake.
Seismicity	seismic hazard for a given area. Low seismicity indicates occurrence risk of few earthquakes; high seismicity indicates risk of large earthquakes.
Structural damage	damage which affects the structural integrity of a given structure and which can lead to the collapse of the structure or its major elements.
Subduction zone	a geological term to describe the zone where one tectonic plate is sliding gradually beneath another plate (e.g. Cascadia subduction zone, Chilean subduction zone).
Subduction earthquake	an earthquake from a source located in a subduction zone.

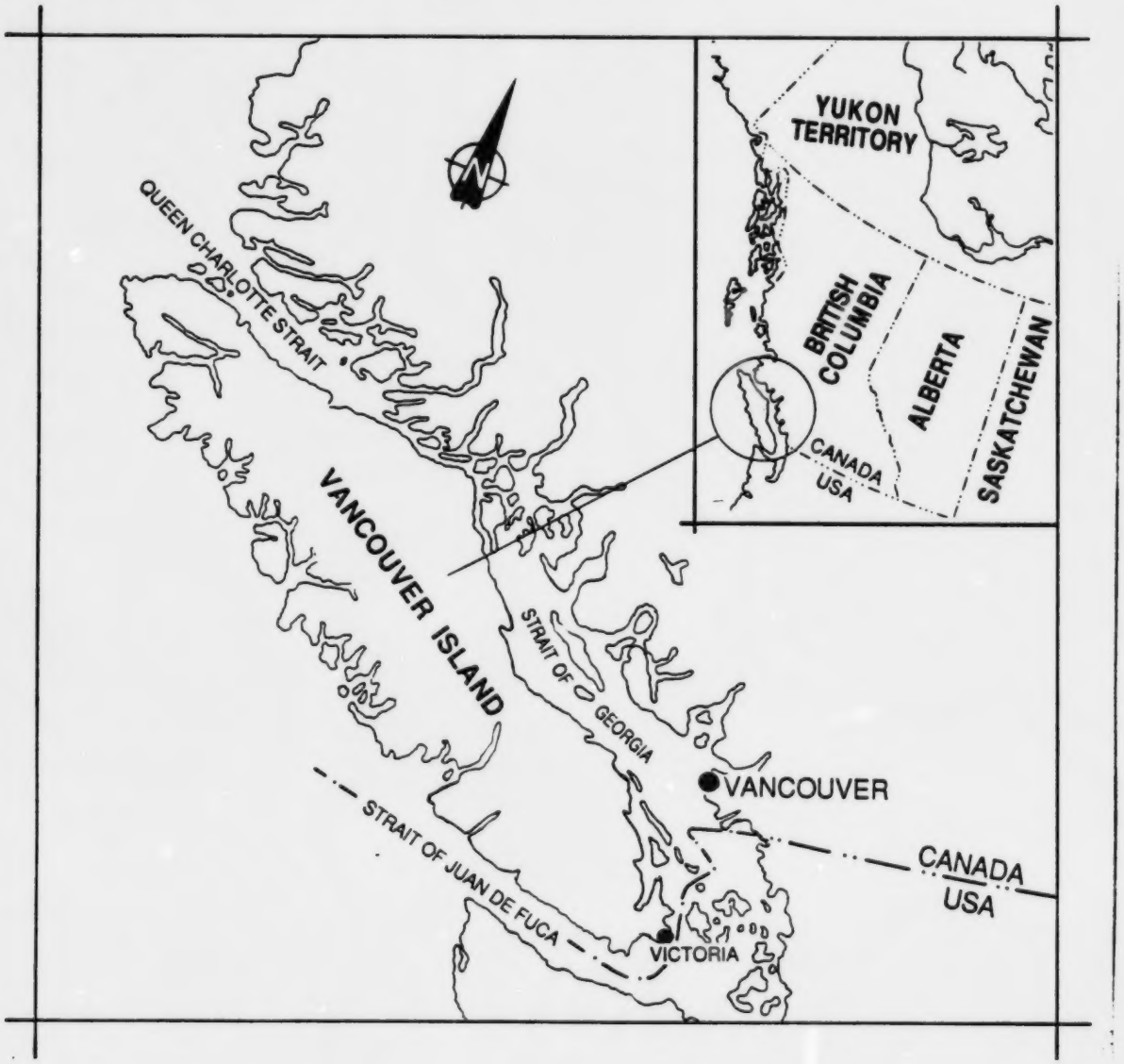

Fig. 1 The Greater Vancouver Area - Geographical Location

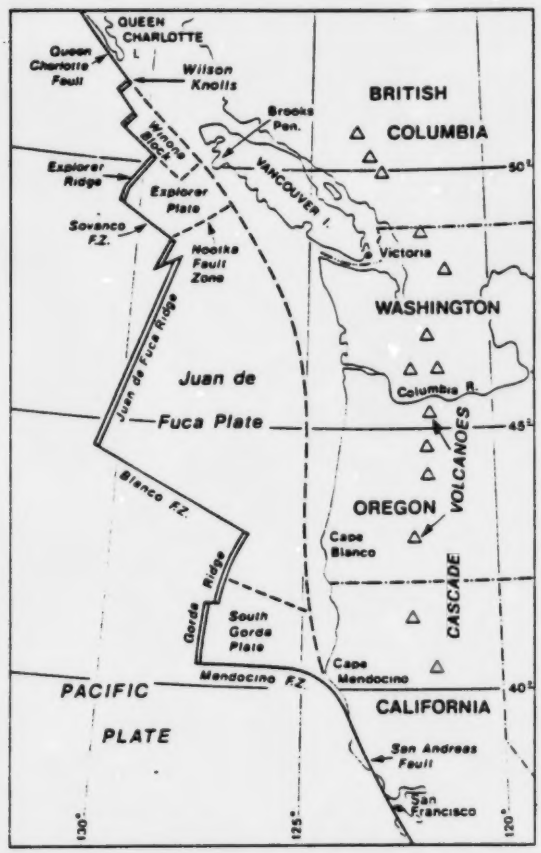

Fig. 2 The Cascadia subduction zone showing the location of the main segment subducting the Juan de Fuca plate and smaller segments at each end (4).

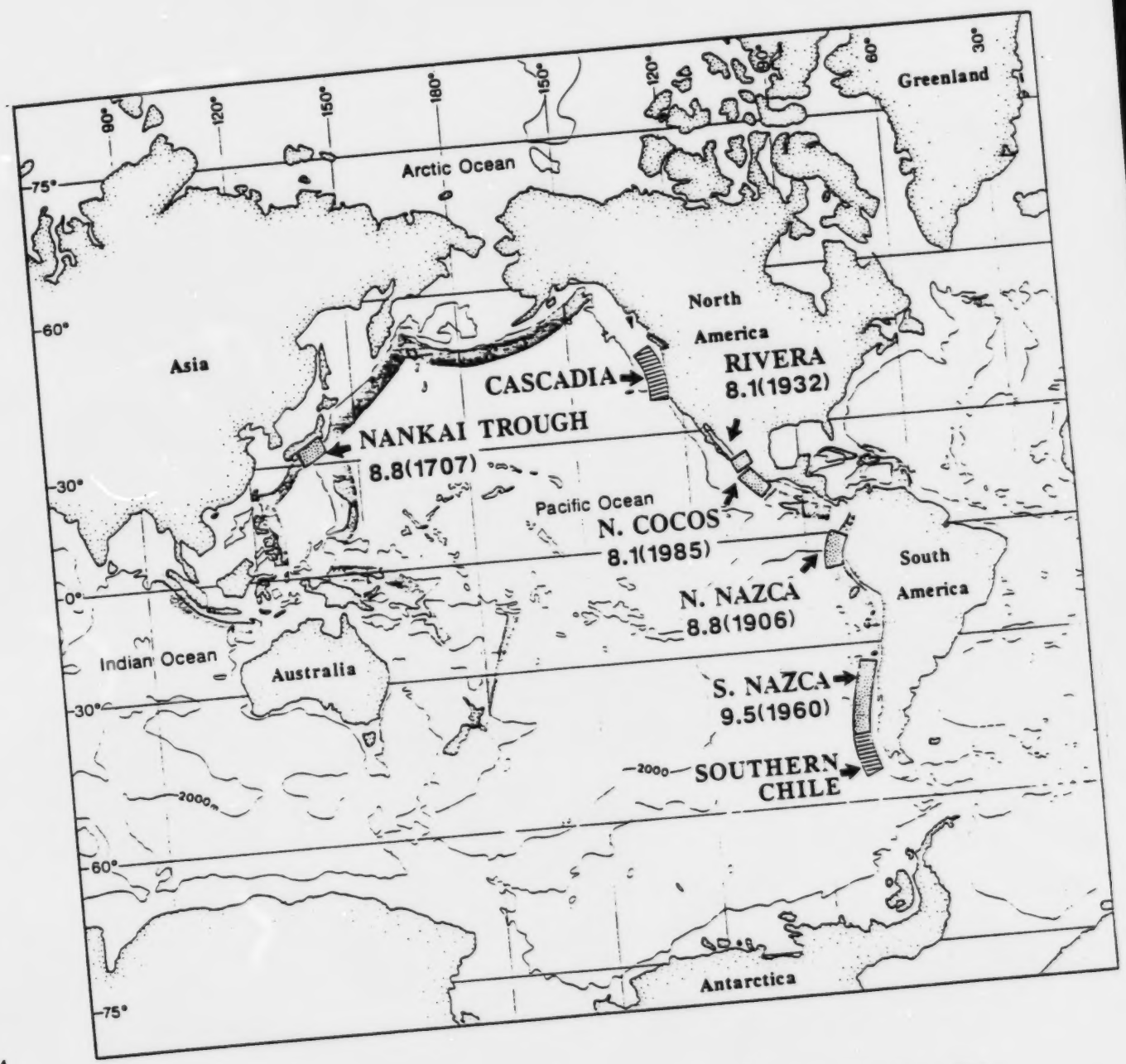

Fig. 3 Subduction zones around the Pacific with younger subducting plates highlighted (4). The magnitude of the largest known earthquake and the year are also indicated.

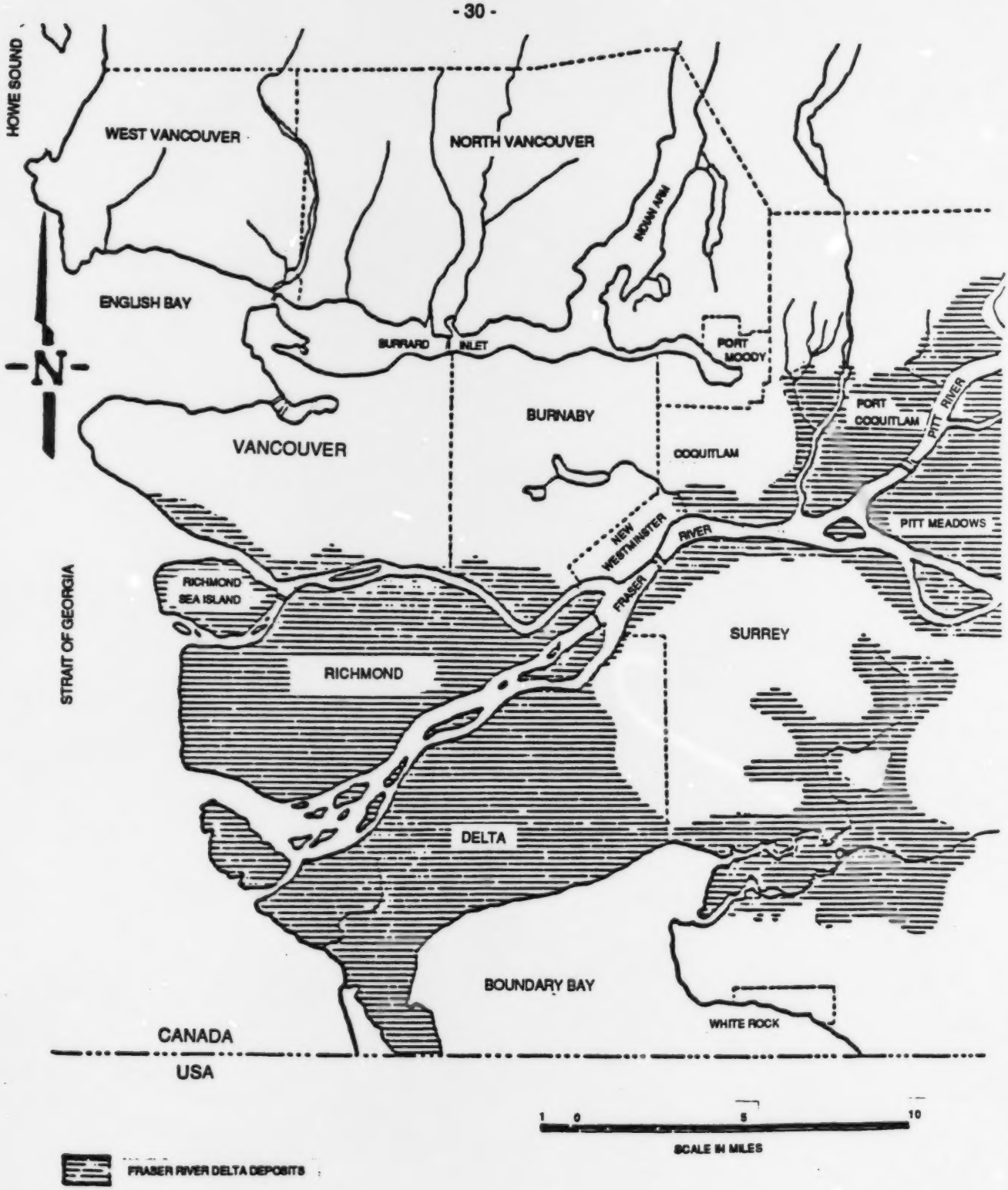

Fig. 4 Fraser River Delta Deposits in the Greater Vancouver Area (5,6)

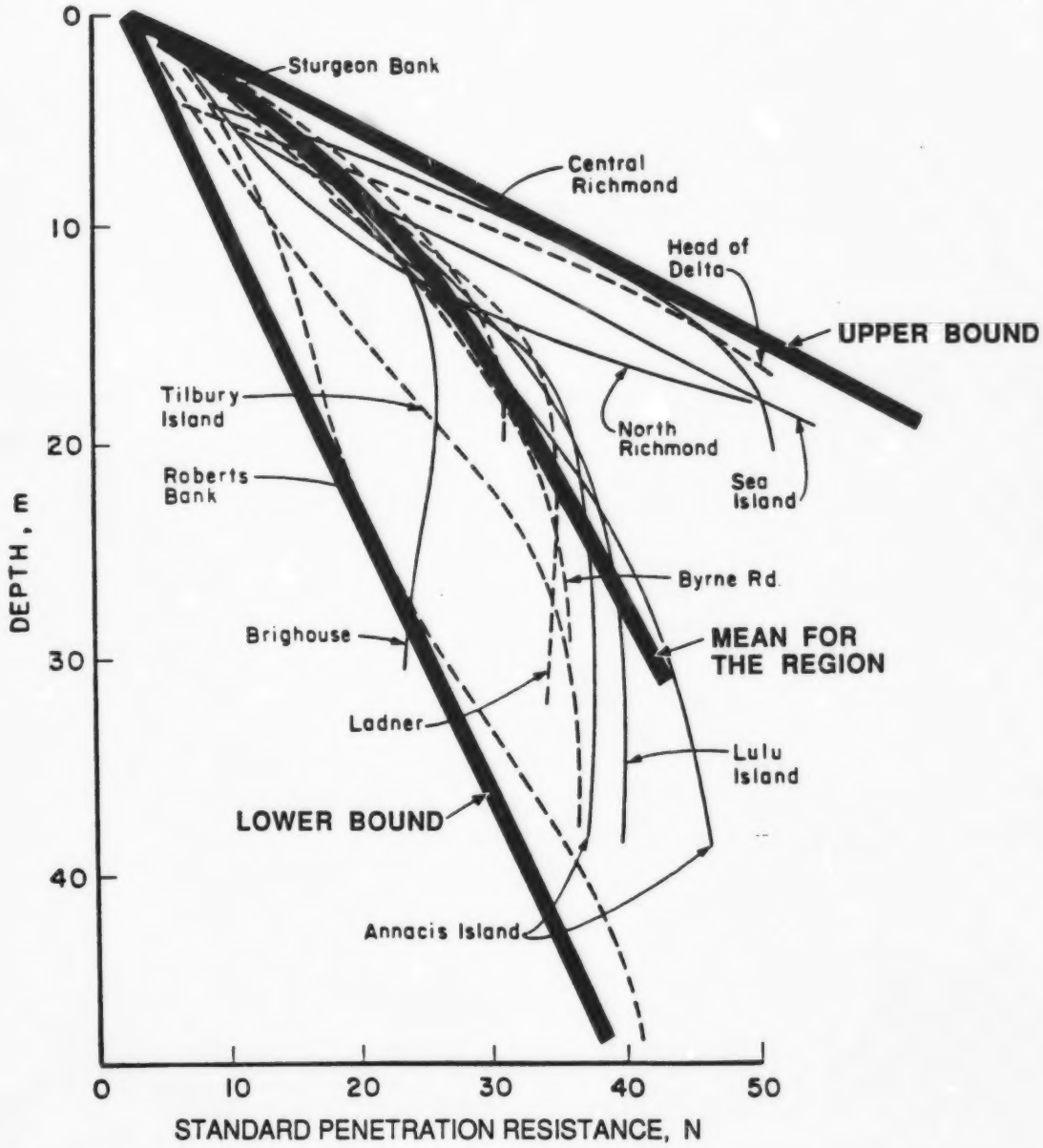

Fig. 5 Mean Standard Penetration Resistance N Values in Richmond and Fraser Delta (9).

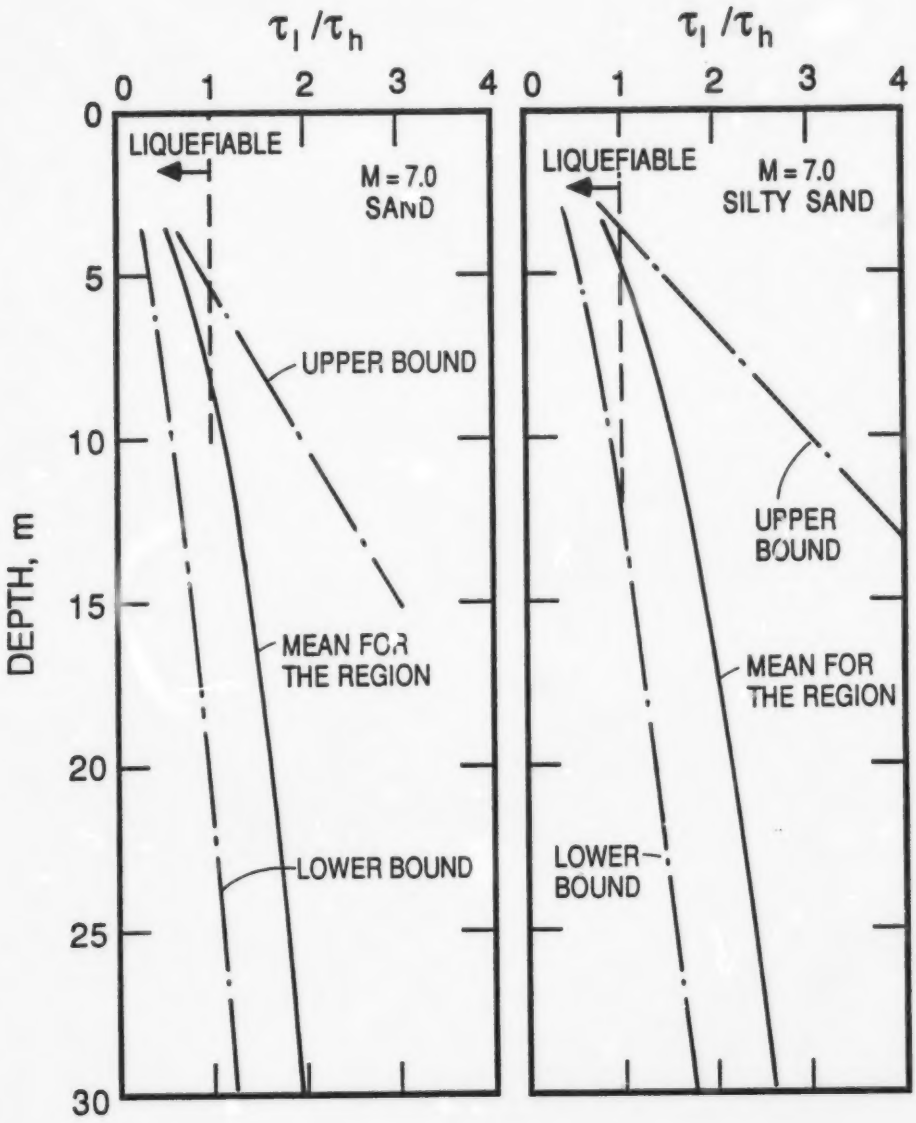

Fig. 6 Liquefaction Potential of Alluvial Deposits in Richmond and Fraser Delta during a Design Earthquake with a_{max} = 0.2g, M=7.

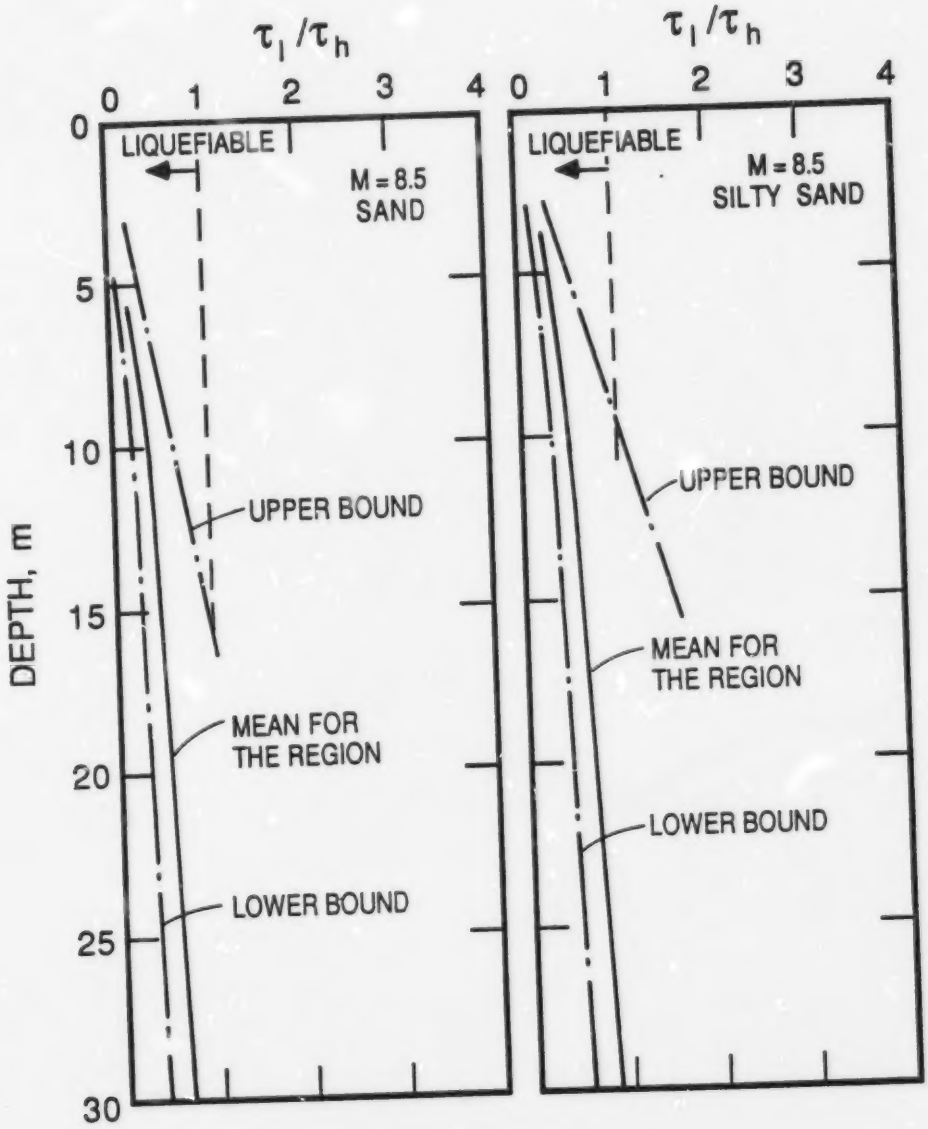

Fig. 7 Liquefaction Potential of Alluvial Deposits in Richmond and Fraser Delta during a "Major Earthquake" with α_{max} = 0.5g, M=8.5

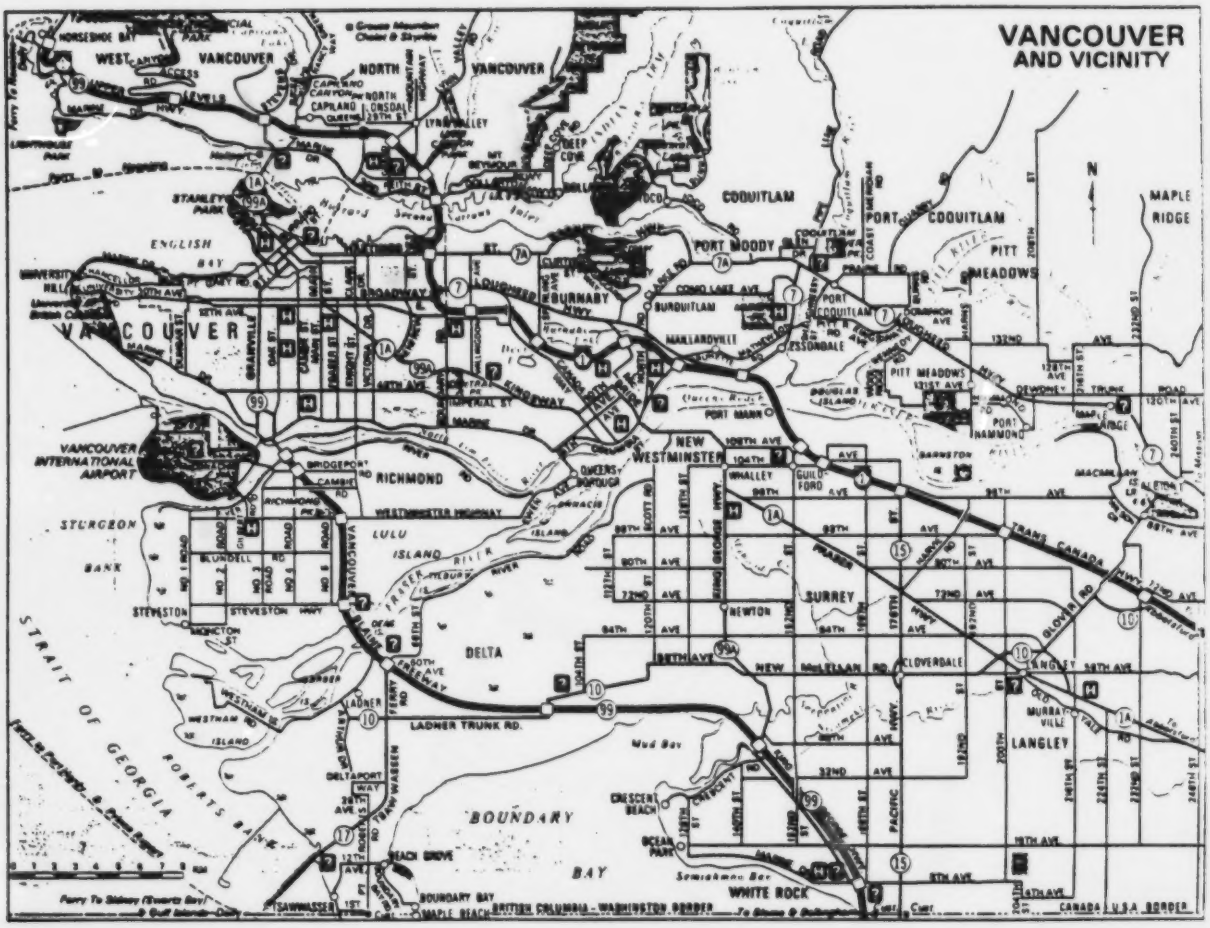

Fig. 8 Vancouver and Vicinity